

# Relation between radio core length and black hole mass for active galactic nuclei

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## ABSTRACT

We explore the relation between the linear length of radio core and the central black hole mass for a sample of radio-loud active galactic nuclei (AGNs). An empirical relation between the size of the broad line region (BLR) and optical luminosity is used to estimate the size of the BLR. The black hole mass is derived from  $H_\beta$  line width and the radius of the BLR on the assumption that the clouds in BLRs are orbiting with Keplerian velocities. A significant intrinsic correlation is found between the linear length of the core and the black hole mass, which implies that the jet formation is closely related with the central black hole. We also find a strong correlation between the black hole mass and the core luminosity.

**Key words:** galaxies:active– galaxies:jets–quasars:general

## 1 INTRODUCTION

Relativistic jets have been observed in many radio-loud AGNs and are believed to be formed very close to the black holes. In currently most favoured models of the formation of the jet, the power is generated through accretion and then extracted from the disc/black hole rotational energy and converted into the kinetic power of the jet (Blandford & Znajek 1977; Blandford & Payne 1982). The disc-jet connection has been investigated by many authors in different ways (Rawlings & Saunders 1991; Falcke & Biermann 1995; Xu & Livio 1999; Cao & Jiang 1999; 2001).

The structure of jets in parsec scales in many AGNs has been revealed by the Very Long Baseline Interferometry (VLBI). The unresolved core might be the base of the jet, and it is optically thick at the observed frequency (Königl 1981), which can successfully explain the fact that the radio emission from the core usually exhibits a flat spectrum. For the nearby AGN M87, one can even resolve their core-jet structure at a length scale of less than 100 Schwarzschild radii at 43 GHz (Junor et al. 1999). VLBI observations are useful to explore the physics at work in jet formation.

Recently, some different approaches are proposed to estimate the masses of the black holes in AGNs, such as the gas kinematics near a hole (see Ho & Kormendy 2000 for a review and references therein). The central black hole mass derived from the direct measurements on the gases moving near the hole is reliable, but unfortunately, it is available only for very few AGNs. For most AGNs, the velocities of the clouds in BLRs can be inferred from the widths of their broad lines.

If the radius of the BLR is available, the mass of the central black hole can be derived from the broad-line width on the assumption that the clouds in the BLR are gravitationally bound and orbiting with Keplerian velocities (Dibai 1981). The radius of the BLR can be measured by using the reverberation-mapping method from the time delay between the continuum and line variations (Peterson 1993; Netzer & Peterson 1997). Long-term monitoring on the source is necessary for applying this method to derive the radius of the BLR, which leads to a small amount of AGNs with measured hole masses in this way. More recently, a tight correlation is found between the size of the BLR and the optical continuum luminosity. One can then estimate the size of the BLR in an AGN from its optical luminosity (Wandel, Peterson & Malkan 1999; Kaspi et al. 1996; 2000). The velocities of the clouds in BLRs can be inferred from the broad line width. So, the mass of the black hole in an AGN can finally be estimated from its  $H_\beta$  width and the optical continuum luminosity (Laor 2000).

Many attentions have been paid on the black hole masses and accretion types, and their relationship with radio emission (McLure & Dunlop 1999; Salucci et al. 1999; Laor 2000; Lacy et al. 2001; Gu, Cao & Jiang 2001; Ho & Peng 2001; Ho 2001). Srianand & Gopal-Krishna (1998) have explored the correlation between the black hole mass and the largest linear radio size for a sample of radio-loud quasars. They use the largest linear radio size as a tracer of source age to study the evolution the central black hole, which is different from our present work. In this work, we perform a statistical analysis on a sample of radio-loud AGNs. The central black hole mass and the linear length

of the VLBI core are derived for all the sources in this sample. In Sect. 2, we describe the sample. Sections 3-5 contain the results and discussion. The cosmological parameters  $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $q_0 = 0.5$  have been adopted in this paper.

## 2 SAMPLE

Our starting sample is a combination of several large VLBI surveys. It consists of:

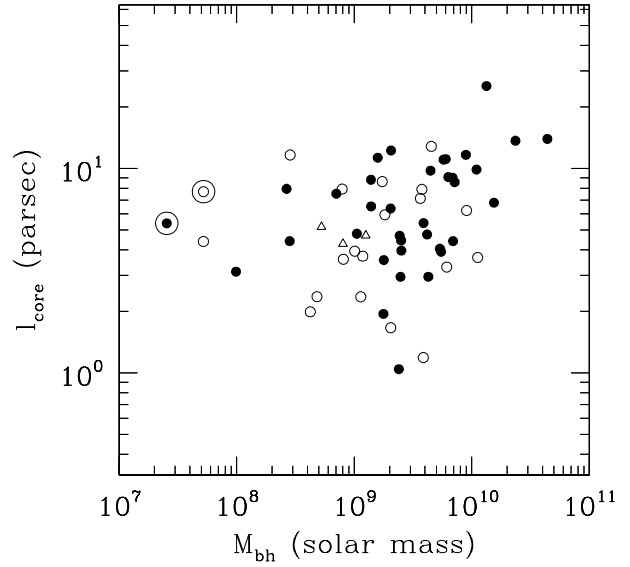
1. Pearson-Readhead sample (Pearson & Readhead 1988, hereafter PR sample), The flux density limit at 5 GHz is 1.3 Jy;
2. the first Caltech-Jodrell Bank VLBI survey (Xu et al. 1995, hereafter the CJ1 sample). It extends the flux density limit of PR sample from 1.3 to 0.7 Jy;
3. the second Caltech-Jodrell Bank VLBI survey (Taylor et al. 1994, hereafter the CJ2 sample), Its flux density limit at 4850 MHz is 0.35 Jy. A combination of flat-spectrum sources in PR sample, the CJ1 and CJ2 samples is given by Taylor et al. (1996);
4. a southern hemisphere VLBI survey of compact radio sources (Shen et al. 1997; 1998). Its flux density limit at 5 GHz is 1 Jy.
5. a large sample of radio reference frame sources observed by the Very Long Baseline Array (VLBA) (Fey, Clegg & Fomalont 1996; Fey & Charlot 1997; 2000);

This combined sample contains more than 500 sources with both measured core lengths and available redshifts. It has included most AGNs with VLBI observations, though it is not a homogeneous sample. We believe that it would not affect the main conclusions of this investigation.

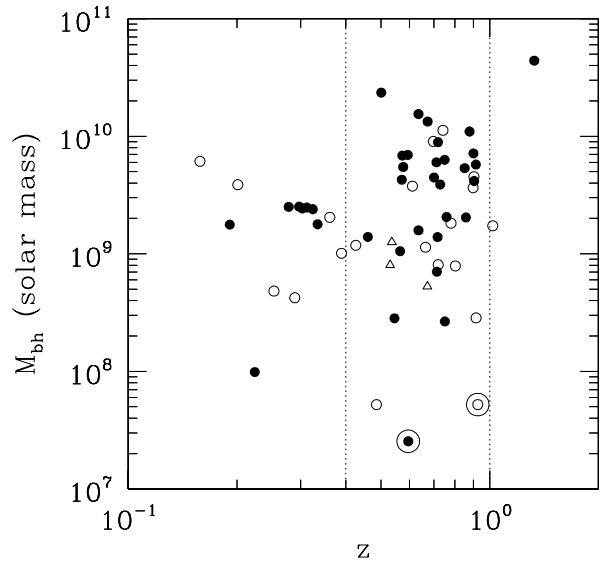
The width of the broad line  $H_\beta$  is necessary in estimating the central black hole mass. We focus on the sources in the starting sample with redshifts in the range  $0 < z < 1.5$ . This constraint limits the starting sample to about 300 sources. We then search the literature, collect all sources luminous than  $M_B = -23$  with available data of  $H_\beta$  profiles. Finally, we have a sample of 59 sources listed in Table 1.

## 3 RESULTS

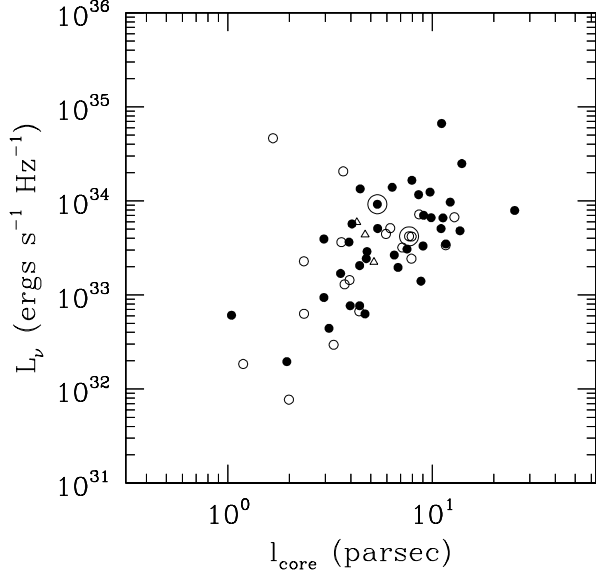
The size of the BLR is derived by using the relation between  $R_{\text{BLR}}$  and the optical continuum luminosity at 5100 Å (Kaspi et al. 2000). The velocity of the clouds in the BLR is estimated from the full width at half maximum (FWHM) by:  $v = 1.5 R_c^{0.1} \times \text{FWHM}(H_\beta)$  (McLure & Dunlop 2001; Lacy et al. 2001), where  $R_c$  is the ratio of the core to extended radio luminosity at 5 GHz in the rest frame of the sources. The motion of the clouds may be anisotropic, and the orientation effect would be important (McLure & Dunlop 2001). The parameter  $R_c$  is an indicator of the jet orientation. The factor  $R_c^{0.1}$  is used to subtract the orientation effect (Lacy et al. 2001). For those sources without measured  $R_c$ , we assume  $R_c = 10$  and  $R_c = 0.1$  for flat-spectrum and steep-spectrum sources respectively (Lacy et al. 2001). The central black hole masses can then be estimated on the assumption of the clouds in BLRs orbiting with Keplerian velocities. All the data are listed in Table 1.



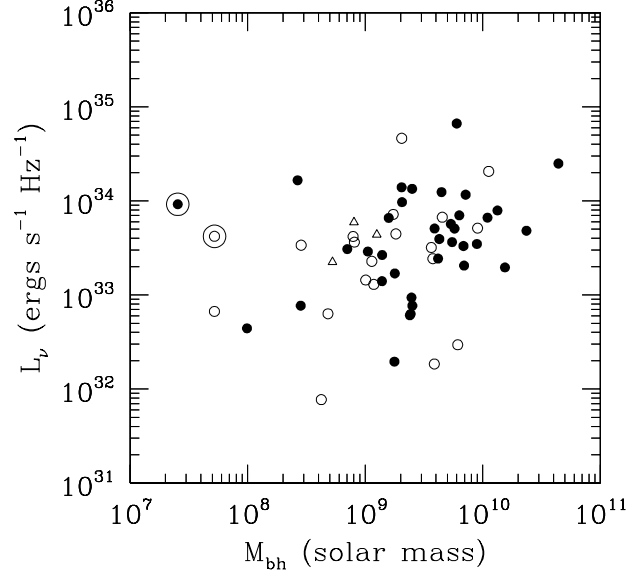
**Figure 1.** The relation between the central black hole mass and the linear length of the VLBI core corrected to the rest frame of the sources. The full circles represent the sources observed at 8.55 GHz, and the open circles represent the sources observed at 5 GHz, while the triangles represent the sources observed at 2.32 GHz. The large open circles represent the sources with  $\text{FWHM}(H_\beta) < 1000 \text{ km s}^{-1}$ .



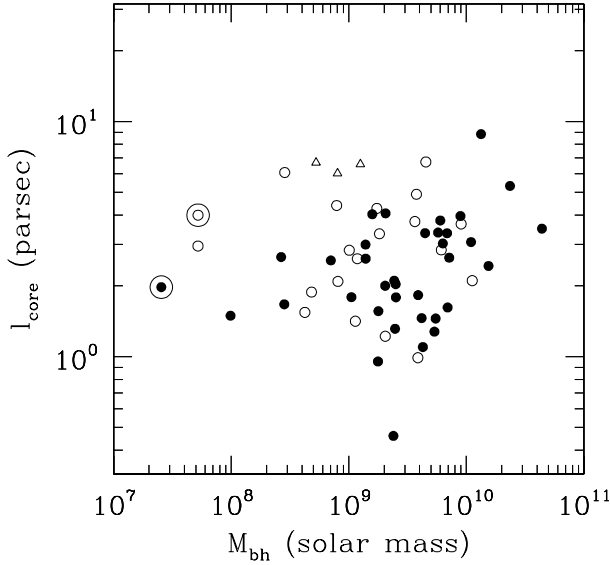
**Figure 2.** The black hole mass versus redshift plane for the sample (symbols as in Fig. 1).



**Figure 3.** The relation between the linear length of the VLBI core and the core luminosity at 5 GHz (symbols as in Fig. 1).

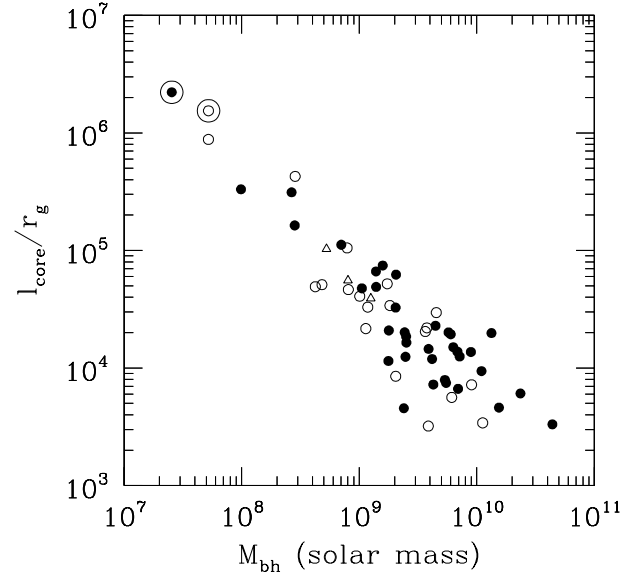


**Figure 5.** The core luminosity at 5 GHz and the central black hole mass relation (symbols as in Fig. 1).



**Figure 4.** Same as Fig. 1, but the linear length of the core has not been correct to the rest frame of the sources.

The angular size of the core varying with the VLBI observing frequency is common in compact extragalactic sources. It is found that the length of the major axis of the core in the nucleus of M81 is proportional to  $\nu_{\text{obs}}^{-0.8}$  (Bietenholz et al. 1996). For 3C345, multi-frequency VLBI observations show that the angular size of the core is proportional to  $\nu_{\text{obs}}^{-1.33}$  (Unwin et al. 1994). Recently, a statistic analysis shows a similar power law relation:  $\theta_{\text{core}} \propto \nu_{\text{obs}}^{-1}$  for a large sample of AGNs (Jiang & Cao, in preparation). The dependence of the core size on the observing frequency can be nat-



**Figure 6.** Same as Fig. 1, but the length of the core is in unit of the Schwarzschild radius (symbols as in Fig. 1).

urally explained in the frame of inhomogeneous sphere/jet models (Marscher 1977; Blandford & Königl 1979; Königl 1981). In this kind of models, the radius at which optically thin emission can be seen from the center varies with frequency as a power law. The sources in our present sample are observed at three different frequencies, and redshifts of the sources range from 0.158 to 1.327. So, we will correct the observed length of the major axis of the core to the

rest frame of the sources. The length of the major axis  $a_e$  observed at  $\nu_e$  in the rest frame of the sources is given by

$$a_e = a_{\text{obs}} \left( \frac{\nu_e}{\nu_{\text{obs}}(1+z)} \right)^{-\beta}, \quad (1)$$

where  $\beta = 1$  is adopted in this work (Jiang & Cao, in preparation).

The linear length of the core is then available:

$$l_{\text{core}} = a_e D_a, \quad (2)$$

where  $D_a$  is the angular diameter distance of the source. We use this formula to convert the angular length to the linear length observed at 5 GHz in the rest frame of the sources (listed in Table 1).

### 3.1 Correlations between $l_{\text{core}}$ and $M_{\text{bh}}$

The core lengths of the sources in our sample are observed at three frequencies: 2.32 GHz, 5 GHz and 8.55 GHz, respectively. We use Eqs. (1) and (2) to calculate the linear length observed at 5 GHz in the rest frame of the sources.

We find that two sources in our sample have very narrow  $H_\beta$  lines ( $\text{FWHM}(H_\beta) < 1000 \text{ km s}^{-1}$ ). The widths of  $H_\beta$  for these two sources approximate to that of the typical narrow lines. It should be cautious on the black hole mass estimate for these two sources, since we cannot rule out the possibility that the  $H_\beta$  line in these two sources may be the narrow component emitted from the narrow line regions (Gu et al. 2001). We therefore rule out these two sources in all the following statistic analyses.

The relation between the linear length  $l_{\text{core}}$  and the central black hole mass  $M_{\text{bh}}$  is plotted in Fig. 1. A significant correlation is found between these two quantities at 99.2 per cent confidence (Spearman rank correlation analysis). The correlation coefficient is  $r = 0.351$ . We present the derived black hole mass as functions of redshift  $z$  for the sample in Fig. 2. A weak correlation is found at 94 per cent confidence between the black hole mass  $M_{\text{bh}}$  and redshift  $z$ . In order to explore whether the correlation between  $l_{\text{core}}$  and  $M_{\text{bh}}$  is caused by the common redshift dependence, we use the Spearman partial rank correlation method (Macklin 1982) to check the correlation. The partial correlation coefficient is 0.25 after subtracting the common redshift dependence. The significance of the partial rank correlation is 1.86, which is equivalent to the deviation from a unit-variance normal distribution if there is no correlation present (Macklin 1982). A summary of the results of partial rank correlation analyses is listed in Table 2. We perform a correlation analysis on the sources in the restricted redshift range  $0.4 < z < 1$ . For this subsample of 41 sources, a correlation at 96 per cent confidence is still present between  $l_{\text{core}}$  and  $M_{\text{bh}}$ , while almost no correlation between  $M_{\text{bh}}$  and  $z$  is found (at 62 per cent confidence). It appears that the correlation between  $l_{\text{core}}$  and  $M_{\text{bh}}$  is an intrinsic one, not caused by the common redshift dependence.

The relation between the linear length of VLBI core and the core luminosity at 5 GHz (K-corrected to the rest frame of the sources) is plotted in Fig. 3. A significant correlation is present between these two quantities at 99.998 per cent confidence (the correlation coefficient  $r = 0.575$ ). The common redshift dependence of these two quantities has certainly

played some roles in this correlation. We use the Spearman partial correlation method to check the correlation. The partial correlation coefficient becomes 0.254 after subtracting the common redshift dependence (the significance of this partial rank correlation is 1.892). The correlation coefficient is 0.51 independent of the black hole mass (the significance of the correlation is 4.099). It implies that the correlation between  $l_{\text{core}}$  and  $L_{\nu_{\text{core}}}$  is an intrinsic one. The partial correlation coefficient of the relation between  $l_{\text{core}}$  and  $M_{\text{bh}}$  is 0.177 independent of core luminosity  $L_{\nu_{\text{core}}}$ . The significance of this partial rank correlation is 1.302 (Macklin 1982).

We then calculate the linear length of the core simply using  $l_{\text{core}}^{\text{obs}} = a_{\text{obs}} D_a$ , i.e., without any correction on the dependence of the core size on observing frequency. The relation between  $l_{\text{core}}^{\text{obs}}$  and  $M_{\text{bh}}$  is plotted in Fig. 4. For those 35 sources observed at the same frequency 8.55 GHz, we find a correlation between  $l_{\text{core}}^{\text{obs}}$  at 97.1 per cent confidence.

### 3.2 Correlation between $L_{\nu_{\text{core}}}$ and $M_{\text{bh}}$

We depict the relation between the VLBI core luminosity (K-corrected to the rest frame of the sources) and the central black hole mass in Fig. 5. A strong correlation is present between  $L_{\nu_{\text{core}}}$  and  $M_{\text{bh}}$  at 99.5 per cent confidence (the correlation coefficient  $r = 0.377$ ). The partial correlation coefficient is 0.287 independent of  $l_{\text{core}}$  (the significance of this partial correlation is 2.152). For the subsample of the sources in the restricted redshift range  $0.4 < z < 1$ , a correlation is present between these two quantities at 98 per cent confidence.

## 4 INTERPRETATION OF THE RESULTS

Königl (1981) proposed an inhomogeneous jet model, in which the magnetic field  $B(r)$  and the number density of the relativistic electrons  $n_e(r, \gamma_e)$  in the jet are assumed to vary with the distance from the apex of the jet  $r$  as  $B(r) = B_1(r/r_1)^{-m}$  and  $n_e(r, \gamma_e) = n_1(r/r_1)^{-n} \gamma_e^{-(2\alpha+1)}$  respectively, and  $r_1 = 1 \text{ pc}$ . If the bulk motion velocity of the jet is  $\beta c$  (corresponding to a Lorentz factor  $\gamma$ ) with an opening half-angle  $\phi$ , and the axis of the jet makes an angle  $\theta$  with the direction of the observer, the projection of the distance from the origin of the jet,  $l_{\text{core}}$ , at which the optical depth to the synchrotron self-absorption at the observing frequency  $\nu_e$  in the rest frame of the sources equals unity, is given by equation (3) in Königl (1981) as

$$l_{\text{core}} = (2c_2(\alpha)r_1 n_1 \phi \csc \theta)^{2/(2\alpha+5)k_m} (B_1 \delta)^{(2\alpha+3)/(2\alpha+5)k_m} \times \sin \theta \nu_e^{-1/k_m} \text{ pc}, \quad (3)$$

where  $c_2(\alpha)$  is the constant in the synchrotron absorption coefficient,  $\delta$  is the Doppler factor, and  $k_m = [2n + m(2\alpha + 3) - 2]/(2\alpha + 5)$ .

We assume that the mass loss rate of the jet is

$$\dot{M}_{\text{jet}} = \eta_j \dot{M}, \quad (4)$$

where  $\dot{M}$  is the accretion rate. We further assume that the magnetic field pressure in the base of the jet can be scaled with the radiation pressure of the disc at radius  $r_d$ :

$$\frac{B^2(r_d)}{8\pi} = \frac{8GM\dot{M}f}{3r_d^3 c} \eta_m. \quad (5)$$

**Table 1.** Data of the core lengths and black hole masses.

Source (1)	z (2)	$\nu_{\text{obs}}$ (3)	$\log(l_{\text{core}})$ (4)	$\text{FWHM}H_{\beta}$ (5)	Refs. (6)	$\log(M_{\text{bh}}/M_{\odot})$ (7)
0056−001	0.717	8.55	0.944	3000	B96	9.143
0110+495	0.389	5	0.595	3641	H97	9.004
0133+476	0.859	8.55	0.804	2697	L96	9.309
0227+403	1.019	5	0.935	1864	H97	9.239
0251+393	0.289	5	0.298	3152	VT95	8.626
0336−019	0.852	8.55	0.607	4876	JB91	9.728
0403−132	0.571	8.55	0.470	4780	C97	9.630
0405−123	0.573	8.55	0.955	3590	C97	9.836
0420−014	0.915	8.55	1.043	3000	B96	9.760
0444+634	0.781	5	0.773	3423	SK93	9.261
0518+165	0.759	8.55	1.088	4876	JB91	9.313
0538+498	0.545	8.55	0.644	1900	GW94	8.451
0554+580	0.904	5	1.108	3797	H97	9.656
0607−157	0.324	8.55	0.018	3518	H78	9.380
0724+571	0.426	5	0.571	2645	VT95	9.073
0730+504	0.720	5	0.555	2981	H97	8.908
0736+017	0.191	8.55	0.288	3400	B96	9.248
0738+313	0.635	8.55	0.832	4800	B96	10.189
0806+573	0.611	5	0.898	4135	H97	9.576
0830+425	0.253	5	0.372	2568	H97	8.683
0859−140	1.327	8.55	1.144	5700	N95	10.643
0923+392	0.698	5	0.794	7200	B96	9.956
0953+254	0.712	8.55	1.045	4012	JB91	9.778
0955+326	0.530	2.32	0.631	1380	B96	8.905
1012+232	0.565	8.55	0.680	2700	B96	9.022
1034−293	0.312	8.55	0.469	4101	S89	9.394
1045−188	0.595	8.55	0.731	622	S93	7.405
1058+629	0.664	5	0.372	2633	H97	9.056
1150+497	0.334	8.55	0.551	4810	B96	9.252
1151+408	0.916	5	1.065	1896	H97	8.455
1156+295	0.729	8.55	0.732	3700	B96	9.590
1226+023	0.158	5	0.517	3520	C97	9.787
1253−055	0.536	2.32	0.671	3100	WB86	9.099
1302−102	0.278	8.55	0.647	3400	B96	9.399
1309+555	0.926	5	0.886	704	H97	7.718
1354+195	0.719	8.55	1.066	4400	B96	9.950
1458+718	0.905	8.55	0.677	3000	B96	9.620
1510−089	0.361	5	0.221	2880	B96	9.310
1531+722	0.899	5	0.853	2764	VT95	9.562
1622+665	0.201	5	0.075	4579	VT95	9.588
1637+574	0.750	8.55	0.957	4620	N95	9.800
1641+399	0.593	8.55	0.644	3560	B96	9.841
1642+690	0.751	8.55	0.900	1845	L96	8.425
1656+053	0.879	8.55	0.994	5000	B96	10.040
1726+455	0.714	8.55	0.876	2953	H97	8.848
1734+363	0.803	5	0.899	3213	H97	8.897
1826+796	0.224	8.55	0.495	1059	H97	7.994
1856+737	0.460	8.55	0.814	4777	H97	9.144
1901+319	0.635	8.55	1.052	2580	GW94	9.200
1915+657	0.486	5	0.642	1204	H97	7.717
1928+738	0.303	8.55	0.671	3360	C97	9.386
2128−123	0.501	8.55	1.135	7050	C97	10.371
2143−156	0.701	8.55	0.989	4073	JB91	9.649
2155−152	0.672	2.32	0.714	1653	S89	8.721
2201+315	0.297	8.55	0.598	3380	C97	9.401
2216−038	0.901	8.55	0.933	3300	N95	9.854
2311+469	0.742	5	0.564	6385	SK93	10.050
2344+092	0.673	8.55	1.403	3900	B96	10.125
2345−167	0.576	8.55	0.592	4999	JB91	9.739

Notes for the table 1. Column (1): IAU source name. Column (2): redshift. Column (3): the observed frequency (in GHz); Column (4): the core size corrected to the rest frame of the sources at 5 GHz (in pc); Column (5): the FWHM of the  $H_\beta$  line (in  $\text{km s}^{-1}$ ); Column (6): references for the line widths; Column (7): the derived black hole masses

#### References:

B96: Brotherton (1996), C97: Corbin (1997), GW94: Gelderman & Whittle (1994), H78: Hunstead et al. (1978), H97: Henstock et al. (1997) JB91: Jackson & Browne (1991), L96: Lawrence et al. (1996), N95: Netzer et al. (1995), S89: Stickel et al. (1989), S93: Stickel et al. (1993), SK93: Stickel & Kühr (1993), VT95: Vermeulen & Taylor (1995), WB86: Wills & Browne (1986).

**Table 2.** Spearman partial rank correlation analysis of the sample. Here  $r_{AB}$  is the rank correlation coefficient of the two variables, and  $r_{AB,C}$  the partial rank correlation coefficient. The significance of the partial rank correlation is equivalent to the deviation from a unit variance normal distribution if there is no correlation present.

Correlated variables: A,B	Variable: C	$r_{AB}$	$r_{AB,C}$	significance
$l_{\text{core}}, M_{\text{bh}}$	$z$	0.351	0.250	1.860
$l_{\text{core}}, M_{\text{bh}}$	$L_{\nu\text{core}}$	0.351	0.177	1.302
$L_{\nu\text{core}}, M_{\text{bh}}$	$z$	0.377	0.287	2.152
$L_{\nu\text{core}}, M_{\text{bh}}$	$l_{\text{core}}$	0.377	0.228	1.693
$l_{\text{core}}, L_{\nu\text{core}}$	$z$	0.575	0.254	1.892
$l_{\text{core}}, L_{\nu\text{core}}$	$M_{\text{bh}}$	0.575	0.510	4.099

We assume  $m = 1$ , and mass conservation in the jet, i.e.,  $n = 2$ . Substituting Eqs. (4) and (5) into (3), we have

$$\begin{aligned}
 l_{\text{core}} = & \left[ 2C_2(\alpha)\alpha\eta_j\pi^{-1}\phi(1 - \cos\phi)^{-1} \csc\theta\gamma_{\text{emin}}^{2\alpha}r_1^{-1}\beta^{-1} \right. \\
 & \times c^{-1} \left. \right]^{2/(2\alpha+5)k_m} \left[ \left( \frac{3}{2\tilde{r}_d} \right)^{1/2} f^{1/2}\eta_m^{1/2}r_1^{-1}c^{1/2} \right]^{\frac{(2\alpha+3)}{(2\alpha+5)k_m}} \\
 & \times \delta^{\frac{2\alpha+3}{(2\alpha+5)k_m}} \nu_e^{-1/k_m} (1.11 \times 10^{17} \eta^{-1} \dot{m})^{\frac{2\alpha+7}{2(2\alpha+5)k_m}} \\
 & \times \left( \frac{M}{M_\odot} \right)^{\frac{2\alpha+7}{2(2\alpha+5)k_m}}, \quad (6)
 \end{aligned}$$

where  $\dot{m}$  is the dimensionless accretion rate in unit of Edington rate, and  $\tilde{r}_d = r_d / \frac{2GM}{c^2}$ . In this work, we have adopted  $k_m = 1$ . It is found that  $l_{\text{core}} \propto M^{0.64}$  for  $\alpha = 1$ . We note that the index is insensitive to the value of  $\alpha$ . The statistic results in Figs. 1 and 6 can therefore be interpreted approximately by the inhomogeneous jet model. In fact, the linear length of the core  $l_{\text{core}}$  is a function of several different physical quantities, which may be the reason that the sources plotted in Fig. 1 are dispersed over a large range.

## 5 DISCUSSION

We find almost no correlation between the black hole mass  $M_{\text{bh}}$  and redshift  $z$  in the restricted redshift range ( $0.4 < z < 1$ ), while a significant correlation is still present between the linear length of the core  $l_{\text{core}}$  and the black hole mass  $M_{\text{bh}}$  for this subsample. The possibility that the correlation we found is caused by the common redshift dependence can be ruled out. The Spearman partial correlation analysis confirms this conclusion. It is therefore an intrinsic correlation.

We have to point out that the correlation between  $l_{\text{core}}$  and  $M_{\text{bh}}$  might be affected by the angular resolution limit of VLBI observations. The linear size of the core is obviously a function of redshift, which is similar to the situation for luminosity. If this is the case, this effect will be important in the correlation analysis due to the common redshift dependence. An analysis on the sources in a narrow restricted

redshift range can reduce this effect, since similar linear resolutions would be available for all sources. Our analyses show that the correlation between  $l_{\text{core}}$  and  $M_{\text{bh}}$  is not caused by the common redshift dependence. It seems that the effect of the angular resolution limit of VLBI observations is not important in our analyses.

It is not surprising that an intrinsic significant correlation is present between the core length  $l_{\text{core}}$  and the core luminosity  $L_{\nu\text{core}}$ , since both the core length  $l_{\text{core}}$  and the core luminosity  $L_{\nu\text{core}}$  scale with the magnetic field strength and particle density in the jet (see Königl 1981 and the discussion in Sect. 4). These physical quantities of the jet might be closely related with the central black hole. The black hole mass governs the physical quantities of the jet, such as magnetic field and particle density, and then the two observed quantities: the core length  $l_{\text{core}}$  and the core luminosity  $L_{\nu\text{core}}$  (Königl 1981).

There is no significant correlation between the linear length  $l_{\text{core}}^{\text{obs}}$  (without frequency correction to the rest frame of the sources) and  $M_{\text{bh}}$  for the whole sample, while a correlation is present only for those sources observed at the same frequency 8.55 GHz. The dependence of the core size on observing frequency seems to be important in the correlation analyses, which is in consistent with inhomogeneous sphere/jet models.

The linear core length  $l_{\text{core}}$  is a measurement on the size of optically thick emission region of the plasma in inhomogeneous sphere/jet models (Marscher 1977; Königl 1981). The length  $l_{\text{core}}$  is mainly determined by the electron number density, the magnetic field strength in the plasma and the bulk velocity of the plasma, which may be regulated by the central black hole mass. It is therefore naturally to expect that a larger black hole has a larger radio emission region. But the slope of the  $M_{\text{bh}} - l_{\text{core}}$  is rather flat, i.e., the length  $l_{\text{core}}$  increases slowly with  $M_{\text{bh}}$  (not a linear relation). We plot the relation between the length  $l_{\text{core}}$  in unit of the Schwarzschild radius  $r_g = 2GM/c^2$  and the hole mass  $M_{\text{bh}}$  in Fig. 6. It shows that the dimensionless linear length  $l_{\text{core}}/r_g$  decreases with the hole mass. As discussed in Sect. 4, the results seem to be consistent with the inhomogeneous

geneous jet model. It is worth noting that a similar trend of  $l_{\text{core}}/r_g - M_{\text{bh}}$  seems to be present for three Seyfert galaxies observed by Ulvestad & Ho (2001). It may imply that the origin of the radio emission from these Seyfert galaxies is similar to that of radio-loud AGNs. Their radio emission is generated by compact jets (Falcke 1996; Falcke & Markoff 2000), though the power of the jets in these Seyfert galaxies is significantly lower than that in the radio-loud AGNs discussed in present work.

It was pointed out that the core luminosity is a good indicator of jet power for core dominated quasars (Cao & Jiang 2001). The intrinsic correlation found in this work between the core luminosity and hole mass confirms some previous similar results (McLure 1999; Laor 2000). The jet formation in an AGN is regulated by the central black hole.

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